# Reactor Core Isolation Cooling Reliability Study

## 1 RCIC Description

When the RCIC system receives an automatic start signal as a result of an actual low RPV water level condition or a manual start, the system functions successfully if the turbine starts and obtains rated speed and pressure, the injection valve opens, and coolant flow is delivered to the RPV until the flow is no longer needed. Failure may occur at any point in this process. For the purposes of this study, the following failure modes were observed in the operating data:

- Maintenance-out-of-service (MOOS) occurs if, because of maintenance activities the RCIC system is prevented from starting during an unplanned demand.

- Failure to start (FTS) occurs if the system is in service but fails to automatically or manually start, obtain rated speed in the turbine, or develop sufficient injection pressure and flow to the reactor pressure vessel.

- Failure to run (FTR) occurs if, at any time after the system is delivering sufficient coolant flow, the RCIC system fails to maintain this flow to the RPV while it is needed.

- Failure to restart (FRS) occurs if, during an unplanned demand and after a successful start and run to restore RPV level, the RCIC system is shut down (manually or as a result of a high level trip), and subsequently is demanded to restart (automatically on low vessel level or manually) and fails to restart. The failure to restart can occur on any restart attempt.

- Failure to transfer during recirculation (FRC) occurs if, during an unplanned demand of the system, the test return-line MOV is opened to divert flow from the RPV to the CST and subsequently fails to close, or the injection valve fails to re-open, resulting in no flow to the vessel for level restoration.

Recovery of failures is important and was considered when estimating system unreliability. To recover from a failure, operators have to recognize that the system is in a failed state, restart it without performing maintenance (for example, without replacing components), and restore coolant flow to the RPV. An example of such a recovery would be an operator (a) noticing that the injection MOV had not opened during an automatic start of the system, and (b) manually operating the control switch for this valve, thereby causing the MOV to open fully and allow coolant flow to the RPV. Recovery for the other failure modes is defined in a similar manner. Each failure was evaluated to determine whether recovery by an operator occurred.

## 2 RCIC System Fault Trees

Estimates of RCIC train unreliability are calculated using the unplanned demands and cyclic tests reported in the LERs. The failure data were used to develop failure probabilities for the observed failure modes.

The demands represent opportunities for RCIC system success. Each failure observed in a RCIC operational phase that was not recovered takes away an opportunity from a following phase. With this in mind, the demands are based on the following logic:

1. For the RCIC system to have the opportunity to start, the system could not be inoperable due to maintenance at the time of the demand. If so, then there is no opportunity for RCIC to start. The opportunities to start consist of the number of initial demands minus any MOOS failures observed. The failure to start the RCIC system was partitioned into FTSI and FTSV to gain additional insights into the reliability for this operational phase and to use as much of the cyclic test data as possible.

2. The next operating event in a RCIC system response deals with FTSV. Therefore, any FTSI failure eliminates an opportunity for FTSV. The FTSV unplanned demand counts differ from the FTSI demands, since the injection valve receives a permissive signal to open only if adequate pump discharge pressure is present and the low RPV water level signal is locked in. Since the injection valve is not tested under the conditions experienced during an unplanned demand, cyclic test data were not used for FTSV.

3. Once the pump has started and the injection valve has opened, the pump is required to run until stopped (FTRI).

4. For the unplanned demands, the failures observed during the run phase have the opportunity to be recovered. Failures observed during the run phase of a cyclic test generally result in the test being terminated, and no effort to recover the failure is attempted. Therefore, no fail to recover entries for the test-related events would be tabulated even if failures had occurred.

5. The restart failure data consists of the number of events that identified restarts of the RCIC system for subsequent coolant injection to the RPV (i.e., long term events) and any failures observed during this operational phase. The probability a restart is required was added to the model, as well as the failure to recover from the restart failure.

6. The FRO failure data refers to the failure to re-open the injection valve. This is required only for some of the longer events. Therefore, the probability of multiple injections was calculated and this was combined with the failure to recover the FRO.

7. The remaining operational phase of the RCIC involves the recirculation mode (FRC). The number of cycles (i.e., transfer during recirculation to injection and back to recirculation) was not provided in the LERs. Additionally, no method to estimate the number of valve cycles was identified that would be defensible. Therefore, the demand count corresponds to the number of missions in which RCIC operated in the recirculation mode.

## 2.1 RCIC Unreliability for an Eight Hour Mission

The unreliability of the RCIC system for conditions requiring long-term operation of RCIC was calculated using the system fault tree model shown in Figure 1. The model reflects the operating mission of RCIC for conditions that rely on RCIC for maintenance of RPV water level. Typically, transients associated with these conditions result from a reactor trip and feedwater being unavailable as the primary source of water for the RPV. Therefore, RCIC is needed for RPV water level maintenance.

Estimates of RCIC unreliability for long-term operation were calculated from the operating experience data. The following failure modes were used in estimating RCIC system unreliability for the long-term mission:

- Maintenance-out-of-service (MOOS)
- Failure To Start—Other than the Injection Valve (FTSI)
- Failure To Start—Injection Valve (FTSV)
- Failure to Recover from FTSI (FRFTSI)
- Failure To Run—Other than the Injection Valve (FTRI)
- Failure to Recover from FTRI (FRFTRI)
- Failure to Restart per Event (LNRS)
- Probability Restart Required (IFRS)
- Failure to Recover from FRS (FRFTRS)
- Failure to Transfer During Recirculation (8 hours) (FTRC)
- Failure to Recover from FTRC (FRFTRC)
- Failure to Reopen Injection Valve (FRO)
- Failure to Recover from FRO (FRFRO)
- Probability of Multiple Injections (PMI)

For the purposes of quantifying the fault tree, the following conditions were assumed:

- A demand to inject coolant to the RPV is received by the RCIC system.
- RCIC is required to restore RPV water level.
- Feedwater and/or other high-pressure makeup systems are not available to restore and maintain RPV water level.
- Restart of the RCIC system is required for subsequent level restoration.
- RCIC operation is required for long-term maintenance of RPV water level.
- RCIC operates in the recirculation mode following restart.

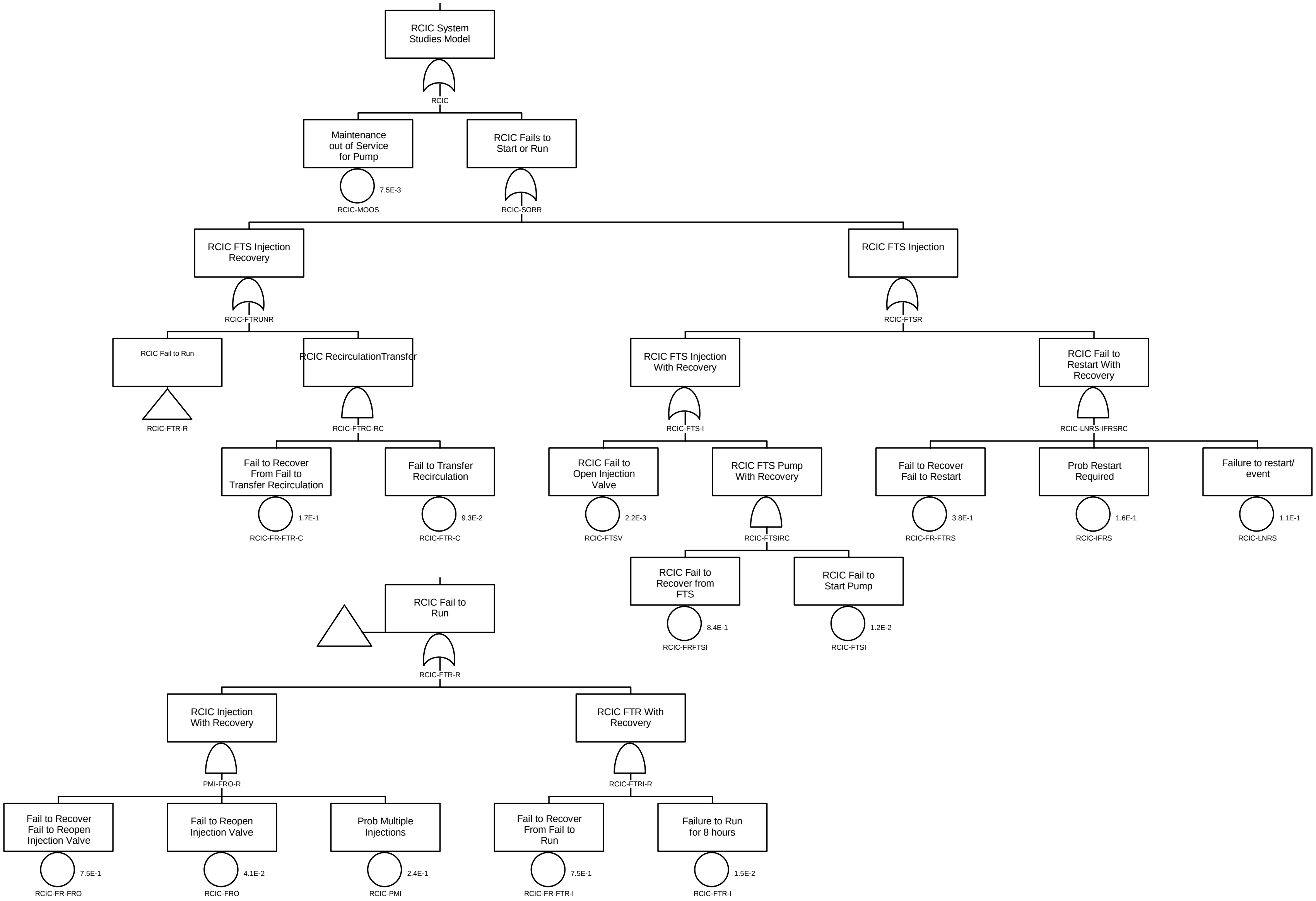


**Figure 1. Unreliability model of RCIC system for an 8-hour mission.**

## 2.2 RCIC Unreliability for a Start Only Mission

The unreliability of the RCIC system for conditions requiring start only operation of RCIC was calculated using the system fault tree model shown in Figure 2. This particular mission is for conditions that do not rely solely on RCIC for maintenance of RPV water level. Typically, these events are associated with conditions that result in a reactor trip with feedwater being available as the primary source of water for RPV. Therefore, RCIC is not needed for RPV water level maintenance. Transients of this nature where RCIC is initially demanded, with feedwater available to restore RPV water level, generally are of very short duration. For these transients, RCIC is started and runs for a short period before it is stopped, either automatically or manually. Based on the operating data, the time of RCIC operation for these types of missions is generally in the 5 to 10 minute range and is less than 15 minutes. These types of demands are referred to as *start only*.

Estimates of RCIC unreliability for start only operation were calculated from the operating experience data. The following failure modes were used in estimating RCIC system unreliability for the start only mission:

- Maintenance-out-of-service (MOOS)
- Failure To Start—Other than the Injection Valve (FTSI)
- Failure to Recover from FTSI (FRFTSI)
- Failure To Start—Injection Valve (FTSV)

For the purposes of quantifying the fault tree, the following conditions were assumed:

- A demand to inject coolant to the RPV is received by the RCIC system.
- RCIC is required to restore RPV water level.
- Feedwater and/or other high-pressure makeup systems are also available to restore and maintain RPV water level.
- RCIC operation is required only for the short term (i.e., less than 15 minutes).

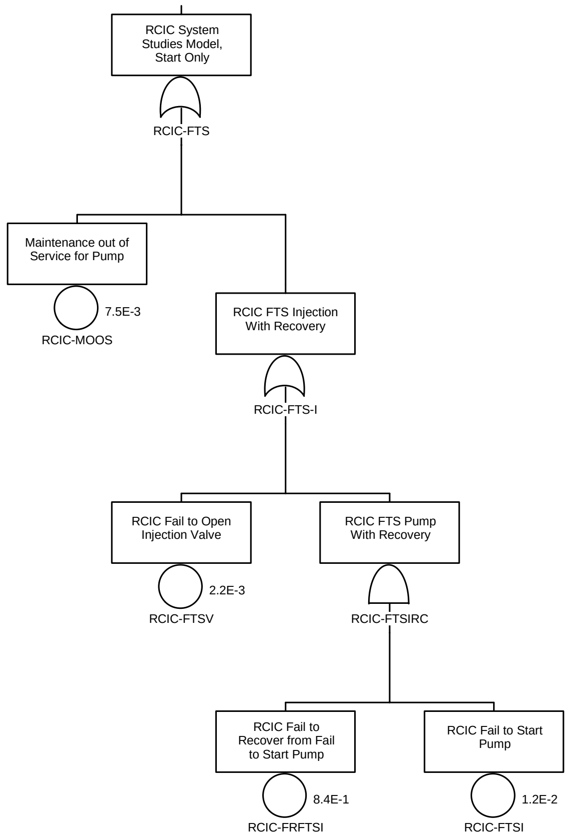


**Figure 2. Unavailability model of RCIC system for a start only mission.**

# 3 Acronyms

| | |
|---|---|
| FR | failure to recover |
| FRC | failure to transfer during recirculation |
| FRS | failure to restart |
| FTR | failure to run |
| FTS | failure to start |
| FTSI | failure to start other than injection valve |
| FTSV | failure to start injection valve |
| IFRS | if restart (probability that a RCIC mission requires a restart) |
| MOOS | maintenance-out-of-service |
| PMI | probability of multiple injection |
| RCIC | reactor core isolation cooling |

# 4 Terminology

*Demand*—An event requiring the RCIC system to inject coolant to the reactor pressure vessel (RPV). This event may be the result of a scheduled (i.e., surveillance test) or an unscheduled (i.e., unplanned) demand. An unplanned demand is either a manual or automatic start because of an actual low RPV water level condition. Engineered safety feature (ESF) actuations of portions of the system (e.g., steam supply isolation valve closures for containment isolation) were not considered as demands.

*Failure*—An inoperability in which the injection function was lost. For estimating the operational unreliability, a subset of the failures was used. (That is, only those that occurred on unplanned actuations or cyclic surveillance tests were used.)

*Failure to run-short term (FTR-ST)*—A FTR with a mission time of less than 15 minutes for RCIC.

*Failure to run-long term (FTR-LT)*—A FTR with a mission time of at least 15 minutes for RCIC.

*Failure to run (FTR)*—Any failure to complete the mission after a successful start. This includes obvious cases of failure to continue running and cases when the system started and injected, tripped off for a valid reason, and then could not be restarted. Excluded from the failure to run events were failures to restart and failures to transfer during recirculation to injection.

*Failure to restart (FRS)*—Failure to restart occurs if, during an unplanned demand, after a successful start and run to restore RPV level, the RCIC system is shut down (manually or as a result of a high level trip), and subsequently the system is demanded to restart (automatically on low vessel level or manually) and fails to restart. The failure to restart can occur on any restart attempt

*Failure to transfer during recirculation (FRC)*—Failure to transfer during recirculation occurs if, during an unplanned demand of the system, the test return-line MOV is opened to divert flow from the RPV to the CST and subsequently fails to close, or the injection valve fails to re-open, resulting in no flow to the vessel for level restoration.

*Failure to start*—Failure of the system to start and inject coolant into the RPV on a valid demand signal.

*Fault*—An inoperability in which the injection function of the system was *not* lost. This includes administrative technical specifications violations such as late performance of a surveillance test.

*If restart (IFRS)* - Probability that a RCIC mission requires the RCIC system to restart (see Failure to restart).

*Inoperability*—An event affecting the RCIC system such that it did not meet the operability requirements of plant technical specifications and therefore was required to be reported in a LER.

*Maintenance-out-of-service (MOOS)*—RCIC system failure attributed to the system being out of service for either preventive or corrective maintenance at the time of the unplanned demand.

*Maintenance unavailability*—Probability that the system is out of service for maintenance at any moment in time.

*Mission time*—The elapsed clock time from the first demand for the system until plant conditions are such that the system is no longer required. PRAs typically assume that RCIC is needed for injection throughout the entire mission time. In the plant operating experience, this period includes not only injection but also recirculation through the test return line or system shut down and restart.

*Operating conditions*—Conditions in which technical specifications require RCIC operability, typically with the reactor vessel pressurized.

*Operating data*—A term used to represent the industry operating experience as reported in LERs. It is also referred to as operating experience or industry experience.

*PRA/IPE*—A term used to represent the data sources (PRAs, IPEs and NUREGs) that describe plant-specific system modeling and risk assessment, rather than a simple focus on operating data.

*P-value*—The probability that the data would be as extreme as it is, assuming the model or hypothesis is correct. It is the significance level (0.05 for this study) at which the assumed model or hypothesis is statistically rejected.

*Recovery*—An act that enables the RCIC system to be recovered from a failure without maintenance intervention. Generally, recovery of the RCIC system was only considered in the unplanned demand events. Each failure reported during an unplanned demand was evaluated to determine whether recovery of the system by operator actions had occurred. Typically, a failure was recovered if the operator was able to reposition a switch, open a valve or reset the governor to restore injection to the RPV. Events that required replacing components were not considered as recoveries. In addition, recovery was not considered during the performance of a surveillance test.

*Unreliability*—Probability that the RCIC system will not perform its required mission. This happens if the system is out of service for maintenance, or if the RCIC system fails to start, run, restart, or transfer during recirculation modes of operation.